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Dummy and Injury Criteria for Aircraft Crashworthiness

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16. Abstract

Since 1988, newly type-certificated aircraft are required to comply with stringent crashworthiness requirements. Central to these more stringent requirements is a dynamic test that assesses the potential for injury for someone exposed to similar conditions. In this report, the techniques and reference values used for measuring the impact protection offered by aircraft seating systems are reviewed. General requirements of a crash dummy are enumerated. The use and limitations of various designs of adult-sized front and side dummies are discussed, and relationships relating dynamic variables measured with a dummy to the probability of an injury are referenced.

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DUMMY AND INJURY CRITERIA FOR AIRCRAFT CRASHWORTHINESS

INTRODUCTION

In 1988, the Federal Aviation Administration (FAA) substantially increased the impact protection requirements for most categories of aircraft [1,2,3][1]. The new airworthiness standards require a dynamic test to assess the "crashworthiness" of an aircraft's seats. Crashworthiness is defined here as the measure of the impact protection that such systems offer. The dynamic tests required in [1,2,3] specify that an anthropomorphic test dummy (ATD, commonly known as a crash dummy) be used, and that dynamic variables measured by the ATD be below values that represent a significant risk of injury.

This paper provides a review and background information on the requirements and available designs of ATDs, and injury criteria to use in assessing the crashworthiness of aircraft systems. The paper is not intended to explain any FAA rules or regulations, nor to provide background on how the amendments of 1988 were determined. The interested reader is referred to [1,2,3] for that information as well as [4,5,6].

Crashworthiness, defined as the measure of the impact protection that a vehicles offers, is typically assessed with a dynamic impact test. In such a test, the seat and/or other vehicle interior components are accelerated with an impact force considered representative of the dynamic conditions encountered in a crash. For aircraft, this is typically a triangular shaped acceleration with a 157 m/s^2 (16 g) peak that occurs 90 milliseconds after the onset of the crash pulse. The reader is advised to refer to the appropriate Advisory Circular material [4,5,6] for full information on the test conditions required. In addition to demonstrating structural capability, the goal of performing this dynamic testing is to measure the potential for an injury resulting from a crash impact.

To achieve this goal, an instrument is needed that reacts similarly to a human being, and which can measure the appropriate dynamic variables to determine the probability of an injury. Two needs resulting from this requirement are the instrument (i.e., the ATD), and injury criteria. An injury criterion relates dynamic variables measured with an ATD to a probability of an injury.

REQUIREMENTS OF AN ATD

An ATD must satisfy several requirements to be a practical, useful device. These requirements are:

1. Biofidelity - how faithfully the ATD simulates a human being.
2. Repeatability - how well an individual ATD will measure the same values when exposed to a repeated set of identical test conditions.
3. Reproducibility - how well two ATDs of identical design produce the same measured value when exposed to the same stimulus.
4. Durability - an ATD must not be destroyed or degraded by an impact test. While a real person might very well be "broken" by the test conditions to which the ATD is exposed, an ATD is required to survive these conditions without being damaged.
5. Calibration Standards - as with any instrument, there must be techniques to insure that the measurements made by an ATD are accurate. Typically, these calibration activities use a precisely defined impact to a particular body region (e.g., dropping the head a prescribed distance onto a surface with a defined compliance) which should produce an expected instrumentation reading within a set of defined confidence limits. Calibration standards for many ATDs are defined in the Code of Federal Regulations [7].

BIOFIDELITY, defined as the measure of how well an ATD simulates human response to the conditions being tested, consists of three sub-components:

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[1]Numbers in [ ] refer to references listed at the end of the paper

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1. Kinematic biofidelity
2. Dynamic compliance biofidelity
3. Injury measure biofidelity

The ATD may be considered as a dynamic linkage system simulating the kinematics of a human being. This implies that as the ATD flails due to crash forces, every part of the ATD must reach the same point in space at the same time with the same velocity as a person exposed to the same conditions. The ATD's inertial distribution and characteristics, and joint characteristics must be similar to those of a human being. This property is the ATD's kinematic biofidelity.

Dynamic compliance biofidelity measures the ATD's ability to impart impact forces that match those of a human being impacting a surface of similar geometry and compliance. This implies that the mass and dynamic stiffness of each part of the ATD's body must match human values. The stiffness characteristics of biological materials typically display very large, non-linear loading rate effects, and frequently biological components consist of loosely coupled masses. Thus, dynamic compliance is a difficult requirement to satisfy, yet it is critical that the ATD's impact interactions be representative.

Injury measure biofidelity refers to the dynamic variables measured by an ATD that are used in relationships that predict the probability of an injury. These relationships, called injury criteria, and discussed later, are derived from human values. If an ATD is to be used to predict the probability of an injury, the values of the dynamic variables measured by the ATD must be similar to those measured in a human being exposed to the same dynamic stimulus.

ANTHROPOMETRY

The size and inertial characteristics of an ATD must represent human values; however, inherent human variability challenges size requirements. Anthropometry is the science which studies the size of human beings. Surveys of the size of human beings have been conducted for the purposes of equipment design, and for standardizing clothing design. An excellent summary of many of these studies is found in [9], and the most recent study of relevance to ATD

design is described in [10]. In designing an ATD, approximately 200 anthropometric measurements of segment lengths, circumferences, masses, moments of inertia, joint locations, and joint ranges of motion are used. The ATD's design represents a particular percentile in all of these measurements.

Typically, an ATD represents the fiftieth percentile in all of these anthropometric measurements, meaning that half of all people are larger, and half of all people are smaller. It is worthy of note that, although a particular individual may have fiftieth percentile stature, they may have eightieth percentile weight, with an arm length that is fortieth percentile. However, a 50th percentile ATD is 50th percentile in all of the anthropometric measurements. There are also differences in anthropometry based on gender. The most common size ATD used is 50th percentile male. For the Hybrid III design (discussed later), fifth percentile female, and ninety-fifth percentile male ATDs are available.

When child restraint devices are impact tested, a variety of ATDs representing different sized children are used. Such ATDs are specified by an age (e.g., a 3 year old ATD), which does not refer to the passage of time since manufacture of the ATD, but rather to the size of a typical child of that age. Child ATDs are not described in this paper.

CURRENTLY AVAILABLE ATDs

Designs of ATDs currently available may be divided into two categories, those for forward impacts, and those for lateral impacts. At any given time, ATDs other than those described here are in development or use for specialized purposes. Those designs are not discussed in this paper. All ATDs allowed for use by the Department of Transportation (both the FAA and the National Highway Traffic Safety Administration (NHTSA) for automotive testing) are specified in [7].

FRONTAL ATDs - There are two designs of frontal ATDs, the Hybrid II, and the Hybrid III. Both were developed by General Motors. The Hybrid II was developed in the late 1960s and early 1970s, and is the ATD specified by the FAA for use in certifying aircraft systems. The Hybrid II has been used for many years in certifying automobiles for NHTSA, the government agency that has regulatory authority over

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the crashworthiness of new automobiles. However, the Hybrid II is being phased out for automotive testing, and replaced with the Hybrid III.

The Hybrid III [8] was developed by General Motors in the mid to late 1970s. Because this ATD features significantly more instrumentation than the Hybrid II, the Hybrid III can be used to monitor many more types of injuries. For example, the Hybrid III can be used to assess the potential for neck injury, lower leg and knee injury, and abdominal injury. The Hybrid II, in contrast, is not equipped to measure threats to these body regions.

The Hybrid III features a flexible lumbar spinal section, designed to better simulate typical seating posture. While the flexible lumbar spine may improve the seating posture of the Hybrid III, it makes it difficult or impossible to measure lumbar spinal compressive loads. Injuries to the spine due to vertical loads and accelerations on a seat are a concern in aviation settings. A dynamic impact test designed to assess the protection that a seat offers against predominantly vertical acceleration injuries is specified in the FAA airworthiness requirements. In this test, a Hybrid II ATD is slightly modified from its automotive test configuration. In the aviation setting, a load cell is placed between the ATD's pelvis and spine to measure spinal compressive loads. The Hybrid III does not currently have this measurement capability, and a modification of the ATD's design will be needed to add this capability.

SIDE ATDs - While the dynamic test conditions to be used for side facing seats in aircraft are specified in the airworthiness regulations, injury criteria for side facing aircraft seats have not been established. The automotive industry is implementing new, more stringent side impact standards. During the development of these more stringent automotive requirements, ATDs were developed to properly simulate a human being exposed to a lateral impact. Three principal designs resulted, each of which is summarized below:

SID - The SID (Side Impact Dummy) was developed during the late 1970s and early 1980s by NHTSA, and is the ATD required by NHTSA to show compliance with Federal Motor Vehicle Safety Standard (FMVSS) 214. The SID is a Hybrid II with a substantially revised thorax. The SID does not have arms, making it difficult or impossible to evaluate shoulder belt retention in an aviation test. The head, neck, pelvis, and lower body of the SID are little changed from the Hybrid II. The SID has been proposed for use in aircraft to show compliance of side facing seats with crashworthiness standards.

BioSID - The BioSID was developed by a committee of the Society of Automotive Engineers (SAE) during the late 1980s. The BioSID is a Hybrid III with a revised thorax. This allows the BioSID to be used to collect neck and lower body measurements. The BioSID has arms allowing for evaluation of shoulder belt retention, but the thorax is non-symmetric, with the ATD's spine located on the side of the ATD opposite the impact.

EuroSID - was developed by the European Common Market during the mid-1980s. While substantially different from the BioSID, the EuroSID is also a Hybrid III with a revised thorax. The EuroSID's thorax is more nearly symmetrical than the BioSID, and features arms, allowing it to be used for shoulder belt retention testing. As with the BioSID, the head and neck of the EuroSID are identical to those used with the Hybrid III. However, some versions of the EuroSID feature a pelvis with substantial instrumentation capability.

INJURY CRITERIA

An injury criterion is defined as a relationship between a measurable dynamic variable and the probability of an injury. Using measurements made by an ATD subjected to an impact test, an injury criterion evaluates the risk of injury to someone subjected to the same environment. An injury criterion must use as input a dynamic variable that can be readily measured by an ATD. This requirement results in most injury criteria using the acceleration of body segments, or internal force as the input dynamic variable. A desirable feature of an injury criterion is that it display a graded response. This means that as the dynamic variable increases in value, so should the risk of injury.

While a desirable feature, this cannot always be obtained. Some body regions, such as the neck, show a highly non-linear injury response where there is a small difference in the input dynamic conditions between a minor and a catastrophic injury.

Considerable information has been published relating dynamic variables to injury. The Society of Automotive Engineers (SAE) issues a standard [11] that provides recommended injury criteria for different parts of the body. The Japanese automobile industry sponsored the development of *The Handbook of Human Tolerance*[12], which provides a thorough review of injury criteria, human anatomy, and ATD design. In conjunction with a research effort to develop an advanced ATD, NHTSA sponsored a thorough review of current injury criteria [13].

The Federal Aviation Regulations (FARs) specify injury criteria to use with the dynamic impact tests specified. These injury criteria are summarized in Table 1; however, it is important to note that there are differences among categories of aircraft in terms of test conditions. In all cases, refer to the current Code of Federal Regulations.

The belt load criterion in Table 1 refers to the tension in the shoulder straps, and is primarily intended as a measure of the threat of a thoracic injury. If no shoulder harness is provided, as is typical in transport category passenger seats, there is no belt tension load limit. If only a single shoulder strap is provided, the belt tension must be less than 7784 N. If there are 2 shoulder straps (as in a 4 point harness), the sum of the tensions in each belt must be less than 8896 N.

The femur compressive load criterion measures the potential for injury to the lower body. The femur is the long bone of the upper leg, between the hip and the knee. In an ATD, a load cell measures compressive loads along the shaft of the femur. If the peak value of these loads is below 10,008 N, serious injury is considered unlikely. The femur load criterion is identical in terms of measurement and interpretation to the criteria developed and used for automobiles. The FARs specify the use of femur injury criteria only for transport category (i.e., Part 25) aircraft.

The spinal compressive load criterion relies on measurements of the compressive load along the length of the ATD's spine. A load cell is placed between the pelvis and the bottom of the spine. If the peak value of these loads is less than 6672 N, spinal injury is considered unlikely. This test is performed with the seat subjected to a vertical acceleration.

The Head Injury Criterion (HIC) is frequently the most challenging standard to meet. HIC [14,15,16,17] is defined by the following equation:

$$HIC = (t_2 - t_1)\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a(t)dt\right]^{-2.5}$$

where:

t_2, t_1 - time limits of integration which maximize the resulting HIC value

$a(t)$ - head center of gravity resultant acceleration as a function of time

When used for evaluating aviation systems, HIC is calculated only when there is head contact, and only during the time interval of the head contact. In automotive testing, HIC is calculated regardless of the presence of head contact, although the maximum

HIC	1000 sec⁻¹	
Belt Loads	7784/8896 N	(1750/2000 lbs)
Spinal Compressive Load	6672 N	(1500 lbs)
Femur Loads	10,008 N	(2250 lbs)

Table 1 — Summary of Aircraft Injury Criteria

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time interval $(t_2 - t_1)$ is limited to 36 milliseconds. If HIC is kept below 1,000, serious head injury is considered unlikely.

HIC was developed based on the Wayne State Tolerance Curve (WSTC) [18]. The WSTC relates head transitional acceleration and time duration, and is reproduced in Figure 1. As proposed by Lissner, the WSTC was based on impact tests conducted with instrumented, embalmed, human cadaveric heads. After impact, an autopsy was performed, and injury was determined, largely based on the presence or absence of a skull fracture. In examining Figure 1, time and acceleration combinations which plot above the line shown are considered injurious, while those which plot below are considered to not represent a risk of a serious head injury.

The WSTC may be interpreted as showing that short time duration, high acceleration, head impact pulses will cause injury, while lower acceleration head impacts require longer durations to do harm. In an effort to derive a simple functional relationship, Gadd [19] plotted the WSTC on a log-log scale. Although a perfect straight line fit did not result, Gadd felt that the approximation was "sufficient at this time." The slope of the straight line fit was 2.5, and this is the weighting factor used in HIC. Gadd proposed a measure, called the severity index (SI), based on raising the time integral of acceleration to the 2.5 power, and restricting this value to less than 1,000 in order to minimize the risk of injury.

Versace presented a mathematical critique of the SI [20] and suggested an alternative method for calculating the index number. Versace argued for using "effective acceleration," defined as $1/t \int a^{2.5} \, dt$, where t is the time duration. Thus, HIC is based on the WSTC, as interpreted by Gadd and later, Versace.

SUMMARY

Techniques used to measure how well a vehicle protects occupants from a serious impact have been described. An instrument that reacts similarly to a human being is used to measure dynamic variables during a test. That instrument is called an ATD, and the ATD must satisfy a number of requirements, including biofidelity, reproducibility, repeatability, durability, and have calibration standards available. ATDs come in a variety of sizes, expressed as percentiles of the population that the device represents. While the most common size is fiftieth percentile, other available sizes represent fifth and ninety-fifth percentile anthropometry.

The ATD is the instrument that measures dynamic variables describing the environment to which a person may be exposed during an impact. Injury criteria are used to relate these measurements to a risk of injury. Injury criteria specify levels above which serious injury to a particular body region is likely. Table 1 summarizes these values for an aircraft including maximum compressive loads in the femur and the
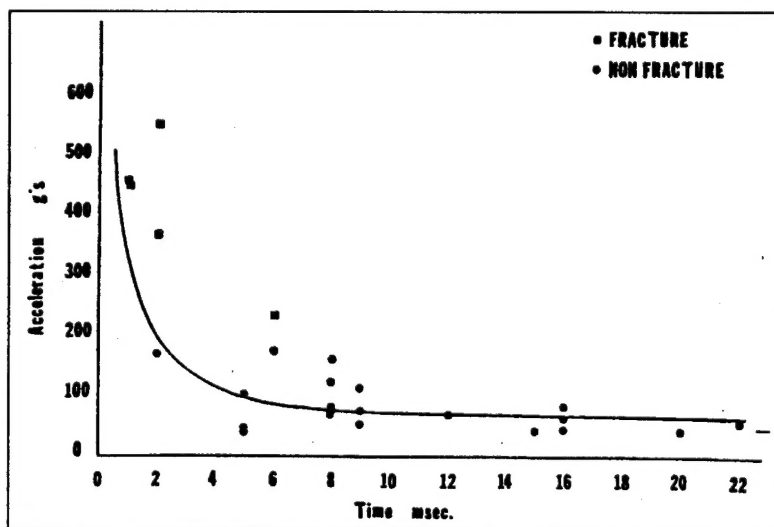

Figure 1— Wayne State Tolerance Curve

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spine, maximum shoulder belt loads, and a maximum value for HIC. HIC, which is based on the WSTC, combines impact acceleration and pulse duration to yield a value that must be kept to less than 1,000 to prevent serious injury.

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